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Comparison of Aerosol Classification from Airborne High Spectral Resolution Lidar and the CALIPSO Vertical Feature Mask

S. P. Burton[1], R. A. Ferrare[1], A. Omar[1], M. A. Vaughan[1], R. R. Rogers[1], C. A. Hostetler[1], J. W. Hair[1], M. D. Obland[1], C. F. Butler[2], A. L. Cook[1], D. B. Harper[1]

[1]NASA Langley Research Center, Hampton VA [2]Science Systems and Applications, Inc.

Knowledge of aerosol composition and vertical distribution is crucial for assessing the impact of aerosols on climate. In addition, aerosol classification is a key input to CALIOP aerosol retrievals, since CALIOP requires an inference of the lidar ratio in order to estimate the effects of aerosol extinction and backscattering. In contrast, the NASA airborne HSRL-1 directly measures both aerosol extinction and backscatter, and therefore the lidar ratio (extinction-to-backscatter ratio). Four aerosol intensive properties from HSRL-1 are combined to infer aerosol type. Aerosol classification results from HSRL-1 are used here to validate the CALIOP aerosol type inferences.

Aerosol typing from HSRL-1 and CALIOP

HSRL uses four aerosol intensive parameters that depend on aerosol type but not amount, to infer aerosol type by comparison with samples of known type.
- lidar ratio at 532 nm
- aerosol depolarization at 532 nm
- backscatter color ratio (532/1064nm)
- ratio of depolarization ratios (1064/532nm)

See also Burton et al. "Aerosol classification of Airborne High Spectral Resolution Lidar Measurements – Methodology and Examples", *AMT* 2012

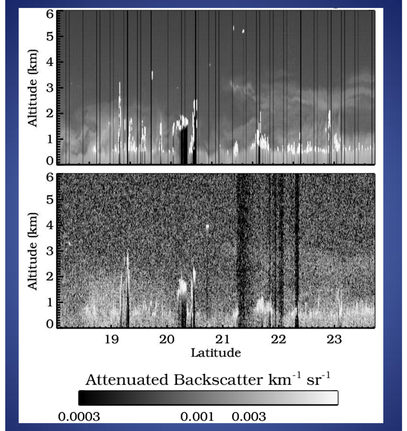
HSRL Aerosol Type	Lidar Ratio at 532 nm (sr) 25-75%iles
Ice	18-33
Pure Dust	45-51
Dusty Mix	29-49
Marine	17-27
Polluted Marine	36-45
Urban	53-70
Smoke	55-73
Fresh Smoke	33-46

CALIOP uses a combination of extensive parameters, estimated intensive parameters, and location information, to infer the lidar ratios at 532 and 1064 nm for detected layers.
- attenuated backscatter
- estimated aerosol depolarization at 532 nm
- layer height
- surface type (ocean, land, tundra)

See also Omar et al. "The CALIPSO Automated Aerosol Classification and Lidar Ratio Selection Algorithm", *JAOT* 2009

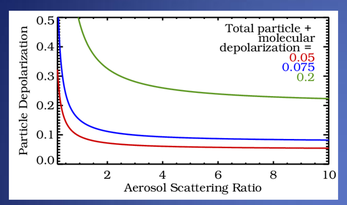
CALIOP Aerosol Type	Lidar Ratio 532 nm (sr)
Marine	20
Desert Dust	40
Polluted Continental	70
Clean Continental	35
Polluted Dust	55
Biomass Burning	70

Measurement Curtains



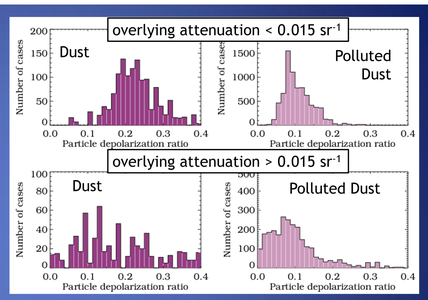
Curtains of attenuated backscatter are shown above for the case on 24 August 2010 (discussed at right) for both CALIOP and HSRL.

Depolarization bias



$$\delta_p^{est} = \frac{\delta_v[(R-1)(1+\delta_m)+1]-\delta_m}{(R-1)(1+\delta_m)+\delta_m-\delta_v}$$

CALIOP aerosol typing depends on a pre-retrieval *estimate* of particle depolarization, which depends on the measured volume depolarization (=molecular + particle) and the *attenuated* aerosol scattering ratio, R. The function is strongly non-linear. R is underestimated when there is attenuation due to aerosol at higher altitudes (in the layer itself or in overlying layers). Underestimation of R causes a high bias in the estimated particle depolarization.



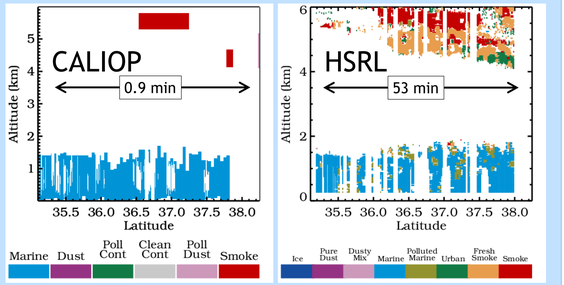
Here are the distributions of all dust and polluted dust cases vs. the true aerosol depolarization, for a month of CALIOP data over CONUS, separated into cases with and without much overlying attenuation. Note that when there is significant attenuation, dust and polluted dust may be selected even in cases having depolarization of only a fraction of a percent. This mistyping indicates that the estimated particle depolarization for these cases was much larger than the true particle depolarization. CALIOP Level 2 Version 4 will include a correction for the attenuation from overlying layers.

Conclusions

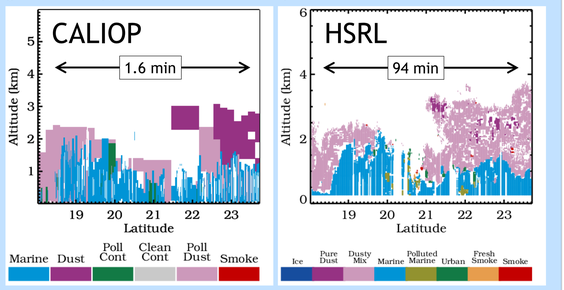
- CALIOP layer detection does not consider aerosol type. Internal boundaries between contiguous aerosol layers often do not accurately reflect transitions between types.
- In 109 coincident flights considered here, multiple HSRL types are required to account for 90% of the AOT in 74% of the CALIOP-defined layers.
- There is agreement in aerosol type between CALIOP and HSRL in 62% of CALIOP marine layers, 54% of CALIOP polluted continental layers, and 80% of CALIOP dust layers.
- There is poor agreement in CALIOP smoke layers, but this will not lead to bias in CALIOP retrieval of aerosol backscatter and extinction.
- There is poor agreement in polluted dust layers.
- Specifically, CALIOP Version 3 includes a bias towards polluted dust and dust in attenuated layers. CALIOP Level 2 Version 4 will include a correction for attenuation from overlying layers.
- Polluted dust is frequently a mixture of dust + marine rather than dust + pollution, leading to overestimated lidar ratio and AOT.

In summary, a future satellite lidar similar to CALIOP, but with the HSRL technique at 532 nm and polarization sensitivity at 1064 nm could provide a significant advance in characterizing the vertical distribution of aerosol for climate and air quality applications.

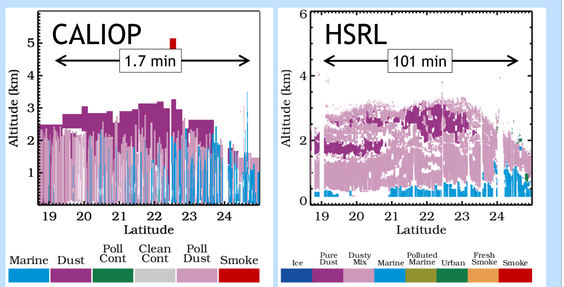
Case Studies



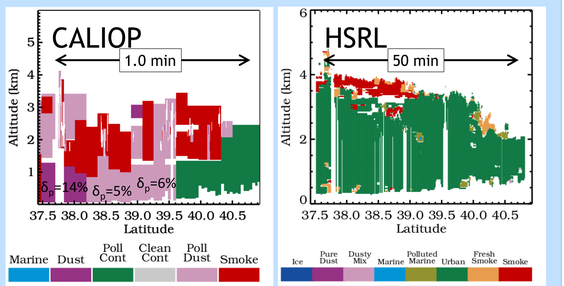
25 June 2006, off the coast of Virginia and Carolina (nighttime). There is good agreement in type for both the marine layer and the elevated smoke layer.



26 August 2010, in the Caribbean Sea (nighttime). Advected Saharan dust layer sitting above the marine boundary layer. Layer detection and typing agree very well. But note that the dust mixture here is dust + marine, not dust + pollution. The measured lidar ratio for dusty mix in this case is 35 sr, compared to 55 sr for CALIOP assignment to polluted dust.



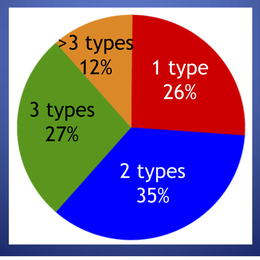
24 August 2010, in the Caribbean Sea (nighttime). Similar aerosol situation to previous case. Aerosol typing again agrees well. But note that internal boundaries between marine and dust mixture are not well characterized. Layers will contain multiple aerosol types. Note that the CALIOP layer detection algorithm does not attempt to detect aerosol types; boundaries between types are defined solely by changes in backscatter intensity.



4 August 2007, near Washington D.C. (daytime). Poor agreement in type characterization. CALIOP scene is less homogeneous than HSRL classification. The boundaries between types produce discontinuities in lidar ratio and retrieved extinction. CALIOP characterizes much of this scene as dust and polluted dust. CALIOP depolarization thresholds for dust and polluted dust are lower than the effective thresholds for HSRL. More importantly, the dust and polluted dust layers in the lower portion of the atmosphere (below about 1300 m) are miscategorized according to the CALIOP thresholds of 7.5% and 20% respectively. See the box at left for the explanation.

Number of HSRL types per CALIOP layer

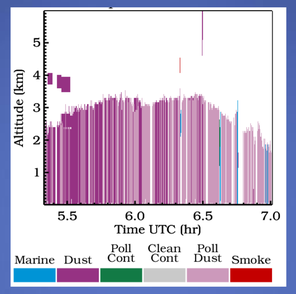
- Multiple HSRL aerosol types are required to account for 90% of the AOT in 74% of the CALIOP-defined layers, considering all 109 coincident flights.
- In only 26% of layers is just 1 type sufficient to account for 90% of the AOT.



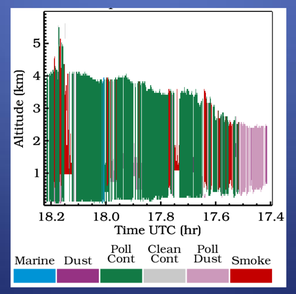
Hybrid HSRL+CALIPSO

In this experiment, HSRL-1 attenuated backscatter data is used as input to the CALIOP processing software, ignoring the higher information content of the HSRL direct extinction measurements. Aerosol classification using the CALIOP algorithms on the higher SNR HSRL "Level 1" is no better. Therefore, the higher *information content* (direct measurements of aerosol intrinsic properties) matters more than the higher SNR of the airborne HSRL.

Ironically, the higher SNR allows CALIOP to detect al most all the aerosol in a single pass through the multi-averaging detection scheme. This results in almost no internal layer boundaries and a single type throughout the boundary layer.

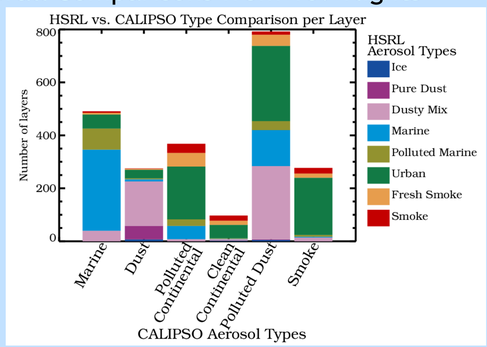


24 August 2010 case processed using HSRL-1 Level 1 data and the CALIOP processing software. Agreement is worse because there are no internal layer boundaries and very little marine aerosol.



4 August 2007 case processed using HSRL-1 Level 1 data and the CALIOP processing software. The improved agreement occurs because there are no internal layer boundaries and the estimated depolarization falls below the threshold for dust in most of the scene.

Overall Comparisons from 109 flights



Comparisons are shown for 109 flight segments of the airborne HSRL along the CALIOP track. Since CALIOP does aerosol typing on a layer-by-layer basis, only the most populous HSRL aerosol type for a given layer are shown.

CALIOP Marine:

62% of layers are dominated by HSRL marine type.

16% of layers are dominated by HSRL polluted marine type.

Polluted marine
- is a mixture of marine and pollution or smoke from offshore flow.
- has a higher mean lidar ratio than marine and will lead to bias in CALIOP retrievals for these cases
- occurs primarily near the coast
- cases may be oversampled in HSRL-CALIOP coincidences, since most flights are not far from land

11% of layers are dominated by HSRL urban type

Of the CALIOP marine layers with at least 2 HSRL types, 33% are marine+polluted marine, 17% are marine+dusty mix, and 15% are marine+urban

CALIOP Desert Dust:

80% of layers are dominated by HSRL pure dust or dusty mix type

Of the CALIOP desert dust layers with at least 2 HSRL types, 35% are dusty mix + dust, 17% are dusty mix + urban, and 14% are dusty mix + marine

CALIOP Polluted Continental:

54% of layers are dominated by HSRL urban type

Urban
- is comprised of small, spherical, absorbing particles
- has a lidar ratio consistent with CALIOP polluted continental
- can be found away from cities

Of mixed layers, 24% are urban+fresh smoke, 18% are urban+smoke, and 12% are urban+dusty mix

CALIOP Polluted Dust

35% of layers are dominated by HSRL dusty mix type.

Dusty mix
- is a mixture of dust plus something else for HSRL
- if mixture contains pollution, will have a higher lidar ratio than pure dust
- if mixture contains marine, will have a lower lidar ratio than pure dust
- CALIOP assumes polluted dust is dust + pollution or dust + smoke and has a higher lidar ratio than desert dust; this can lead to bias in CALIOP retrievals in some cases

36% of layers are dominated by HSRL urban type.

17% of layers are dominated by HSRL marine type.

Of mixed layers, 20% are dusty mix+urban, 17% are dusty mix+marine, 12% are dusty mix+pure dust, and 11% are urban+fresh smoke

For more on polluted dust, see case studies

CALIOP Smoke

13% of layers are dominated by HSRL smoke or fresh smoke

78% of layers are dominated by HSRL urban
- CALIOP smoke and CALIOP polluted continental have the same 532 nm lidar ratio, so mistyping would not cause bias in CALIOP aerosol retrievals
- Some of the difference may be due to CALIOP typing rules, which require all non-depolarizing elevated layers to be smoke
- it is also relatively difficult to separate urban from smoke using HSRL-1 measurements, in part due to similar lidar ratio values, so not all of this disagreement is necessarily CALIOP mistyping
- Smoke vs. Urban is a topic of ongoing study. HSRL-2 measurements (3 extinction + 2 backscatter wavelengths) are expected to have greater ability to separate these types. See posters A13K-0336 Hostetler et al. and A33A-0121 Müller et al.

Of mixed layers, 30% are smoke+urban, 22% are fresh smoke+urban, 19% are urban+dusty mix, and 11% are urban+polluted marine

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